

Correlation of the Quasi-Periodic Oscillation Frequencies of White Dwarf, Neutron Star, and Black Hole Binaries

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ABSTRACT

Using data obtained in 1994 June/July with the *Extreme Ultraviolet Explorer* deep survey photometer and in 2001 January with the *Chandra X-ray Observatory* Low Energy Transmission Grating Spectrograph, we investigate the extreme-ultraviolet (EUV) and soft X-ray oscillations of the dwarf nova SS Cyg in outburst. We find quasi-periodic oscillations (QPOs) at $\nu_0 \approx 0.012$ Hz and $\nu_1 \approx 0.13$ Hz in the EUV flux and at $\nu_0 \approx 0.0090$ Hz, $\nu_1 \approx 0.11$ Hz, and possibly $\nu_2 \approx \nu_0 + \nu_1 \approx 0.12$ Hz in the soft X-ray flux. These data, combined with the optical data of Woudt & Warner for VW Hyi, extend the Psaltis, Belloni, & van der Klis $\nu_{\text{high}}\text{--}\nu_{\text{low}}$ correlation for neutron star and black hole low-mass X-ray binaries (LMXBs) nearly two orders of magnitude in frequency, with $\nu_{\text{low}} \approx 0.08 \nu_{\text{high}}$. This correlation identifies the high-frequency quasi-coherent oscillations (so-called “dwarf nova oscillations”) of cataclysmic variables (CVs) with the kilohertz QPOs of LMXBs, and the low-frequency QPOs of CVs with the horizontal branch oscillations (or the broad noise component identified as such) of LMXBs. Assuming that the same mechanisms produce the QPOs in white dwarf, neutron star, and black hole binaries, we find that the data exclude the relativistic precession model and the magnetospheric and sonic-point beat-frequency models (as well as *any* model requiring the presence or absence of a stellar surface or magnetic field); more promising are models that interpret QPOs as manifestations of disk accretion onto any low-magnetic field compact object.

Subject headings: accretion, accretion disks — novae, cataclysmic variables — stars: individual (SS Cygni) — stars: neutron — stars: oscillations — X-rays: binaries

1. Introduction

Rapid periodic oscillations are observed in the optical flux of high accretion rate (“high- \dot{M} ”) cataclysmic variables (CVs) (nova-like variables and dwarf novae in outburst) (Patterson 1981; Warner 1995a,b). These oscillations have high coherence ($Q \approx 10^4\text{--}10^6$), short periods ($P \approx 7\text{--}40$

s), low amplitudes ($A \lesssim 0.5\%$), and are sinusoidal to within the limits of measurement. They are referred to as “dwarf nova oscillations” (DNOs) to distinguish them from the longer period, low coherence ($Q \approx 1\text{--}10$) quasi-periodic oscillations (QPOs) of high- \dot{M} CVs, and the longer period, high coherence ($Q \approx 10^{10}\text{--}10^{12}$) oscillations of DQ Her stars. DNOs appear on the rising branch of the light curve of dwarf nova outbursts, typically persist through maximum, and disappear on the declining branch of the light curve. The period of the oscillation decreases on the rising branch and increases on the declining branch, but because the period reaches minimum about one day after maximum optical flux, dwarf novae describe loops in plots of oscillation period versus optical flux.

Rapid periodic oscillations have been detected in the flux of numerous high- \dot{M} CVs, but the dwarf nova SS Cyg in outburst is one of the best studied. Oscillations in the optical flux have been detected with periods ranging from 7.3 s to 11 s (Patterson, Robinson, & Kiplinger 1978; Horne & Gomer 1980; Hildebrand, Spillar, & Stiening 1981; Patterson 1981), and oscillations in the extreme-ultraviolet (EUV) and soft X-ray flux have been detected with periods ranging from 2.8 s to 11 s in data from *HEAO 1*, *EXOSAT*, the *Extreme Ultraviolet Explorer (EUVE)*, and *ROSAT* (Córdova et al. 1980, 1984; Jones & Watson 1992; Mauche 1996; van Teeseling 1997; Mauche & Robinson 2001; Mauche 2002a). Mauche (1996, 2002a) showed that the EUV oscillation period is a single-valued function of the EUV flux, explained the loops observed in plots of oscillation period versus optical flux as the result of the delay between the rise of the optical and EUV flux at the beginning of dwarf nova outbursts (Mauche, Mattei, & Bateson 2001), and so provided strong evidence for the proposal, first mooted by Patterson (1981), that the oscillation period depends solely on the mass-accretion rate onto the white dwarf. Mauche & Robinson (2001) observed “frequency doubling” of the EUV oscillation of SS Cyg during the rising branch of its 1996 October outburst, demonstrated that the optical and EUV oscillation periods are equal, and that their relative phase delay is consistent with zero.

In this communication, we present an analysis of observations of SS Cyg in outburst obtained in 1994 June/July with the *EUVE* deep survey (DS) photometer and in 2001 January with the *Chandra X-ray Observatory* Low Energy Transmission Grating Spectrograph (LETGS). In §2 we present the observations and data analysis, finding that the EUV flux was oscillating at frequencies $\nu_0 \approx 0.012$ Hz and $\nu_1 \approx 0.13$ Hz, while the soft X-ray flux was oscillating at frequencies $\nu_0 \approx 0.0090$ Hz, $\nu_1 \approx 0.11$ Hz, and possibly $\nu_2 \approx \nu_0 + \nu_1 \approx 0.12$ Hz. In §3 we discuss these results in the context of similar results from optical observations of the dwarf nova VW Hyi in outburst and X-ray observations of neutron star and black hole low-mass X-ray binaries (LMXBs). As first pointed out by Warner & Woudt (2002a,b), white dwarf, neutron star, and black hole binaries share a common correlation in the frequencies of their QPOs, extending over nearly five orders of magnitude in frequency. The implications of this result for QPO models are discussed, we discuss how additional observations of CVs can provide unique and quantitative tests of QPO models, and close in §4 with a summary.

2. Observations and Data Analysis

2.1. Chandra LETGS

Our pre-approved target-of-opportunity *Chandra* Low Energy Transmission Grating (LETG) and High Resolution Camera (HRC) observation of SS Cyg was performed between 2001 January 16 21^h13^m and January 17 10^h50^m UT during the plateau phase of a wide normal (asymmetric) dwarf nova outburst that began on January 12. When the observation began, SS Cyg had been at maximum optical light ($V \approx 8.5$) for approximately 3 days; long enough, given the delay of 1.5 days between the rise of the optical and EUV light curves of SS Cyg (Mauche, Mattei, & Bateson 2001), for the EUV/soft X-ray flux to have reached maximum and for the system to have reached a quasi-steady-state. Indeed, the zero- and \pm first-order LETG/HRC count rates were observed to be roughly constant throughout the 47.3 ks observation at 1.5 and 4.9 counts s⁻¹, respectively.

The files used for this analysis were created on 2002 January 7 by the pipeline data reduction software using CIAO 2.0 with ASDCS version 6.5.1. Events were extracted from the level 2 evt file, and the mean spectrum and source and background region masks were extracted from the level 2 pha file. The mean LETG spectrum contains two distinct components: (1) a hard component shortward of 40 Å consisting of a bremsstrahlung continuum and emission lines of H- and He-like C, N, O, Ne, Mg, and Si and L-shell Fe (most prominently Fe XVII) and (2) a soft component extending from 42 Å to 120 Å that appears to consist of a continuum significantly modified by a forest of emission and absorption features (possibly even P Cygni profiles). In the 72–120 Å wave band, the LETG spectrum is essentially identical to that measured by the *EUVE* short wavelength (SW) spectrometer during the 1993 August (Mauche, Raymond, & Mattei 1995) and 1996 October (Wheatley, Mauche, & Mattei 2002) outbursts of SS Cyg. These hard and soft components of the X-ray spectrum of SS Cyg are understood to be due to the optically thin and optically thick portions of the boundary layer between the disk and the surface of the white dwarf.

To investigate the temporal properties of the hard and soft X-ray flux of SS Cyg, we processed the \pm first-order LETG events as follows. First, we created a list of source and background events by filtering the events with the source and background region masks. Second, we applied a wavelength filter that excluded events near the HRC chip gaps: for the positive order, events with wavelengths $\lambda = 60.0$ – 67.5 Å were excluded, while for the negative order, events with wavelengths $\lambda = 49.8$ – 57.2 Å were excluded. Without this filter, a portion of the soft component of the spectrum moves on and off the HRC chips, and so produces signals in the power spectra at the spacecraft dither periods of 707 s and 1000 s. Third, various wavelength cuts were applied to isolate the hard ($\lambda = 1$ – 42 Å) component of the spectrum, the soft ($\lambda = 42$ – 120 Å) component of the spectrum, and various subsets thereof (see below). Events passing these filters were used to create background-subtracted light curves with 1 s time resolution, and power spectra of these light curves were examined for evidence of periodic flux modulations. Consistent with more sensitive searches by *HEAO-1* (Swank 1979), *ASCA* (Nousek et al. 1994), *Ginga* (Ponman et al. 1995), and the *Rossi X-ray Timing Explorer* (*RXTE*) (Wheatley, Mauche, & Mattei 2002), no periodic signal was detected in the hard

X-ray light curves. In contrast, strong periodic signals were detected in the soft X-ray light curves: as shown in the upper panel of Figure 1, the power spectrum of the soft X-ray light curve shows excess power at frequencies $\nu_0 \approx 0.0090$ Hz and $\nu_1 \approx 0.11$ Hz, indicating the presence of oscillations at periods $P_0 \approx 110$ s and $P_1 \approx 9.1$ s. To investigate these oscillations more closely, we divided the soft X-ray light curve into 47 consecutive 1 ks intervals and calculated their power spectra. Although the individual power spectra are rather noisy, the $\nu_1 \approx 0.11$ Hz oscillation typically appears as a single $\Delta\nu = 0.001$ Hz peak with a frequency in the range $\nu_1 = 0.109\text{--}0.112$ Hz. The mean of these 47 consecutive 1 ks power spectra is shown in the middle panel of Figure 1. In addition to the peaks at $\nu_0 \approx 0.0090$ Hz and $\nu_1 \approx 0.11$ Hz, there appears to be a shoulder on the higher-frequency peak extending to $\nu \approx 0.12$ Hz. To account for the observed frequency evolution, we scaled the frequency vectors of the 47 power spectra by the instantaneous frequency of the dominant ν_1 oscillation. The mean of these scaled power spectra is shown in the lower panel of Figure 1. Note that most of the power of the ν_1 oscillation now lies in a single frequency bin, there is no excess power in the first harmonic $2\nu_1$ or subharmonic $\nu_1/2$ (i.e., the dominant ν_1 oscillation is sinusoidal to high degree), and the lower-frequency peak lies at $\nu_0/\nu_1 \approx 0.088$.

2.2. EUVE DS Photometer

This is not the first time that multiple periodicities have been seen in the short wavelength flux of SS Cyg. In the power spectrum of the *EUVE* DS count rate light curve of the 1994 June/July outburst of SS Cyg, Mauche (1997b) noted the presence of oscillations at $\nu_0 \approx 0.012$ Hz, $\nu_1 \approx 0.13$ Hz, and its first harmonic $2\nu_1$. Furthermore, he noted that the harmonic peak was present in data from only the first part of the observation, and suggested that the low-frequency peak is due to the spin of the white dwarf. To revisit these issues, we reexamined the DS data from the second part of the *EUVE* observation (between 1994 June 29 0^h49^m and July 3 9^h19^m UT). Background-subtracted light curves were derived from 37 15 ks orbits, 37 power spectra were calculated, and the mean power spectrum derived. As shown in the upper panel of Figure 2, peaks in this power spectrum occur at frequencies $\nu_0 \approx 0.012$ Hz and $\nu_1 \approx 0.13$ Hz, indicating the presence of oscillations in the EUV flux of SS Cyg at periods $P_0 \approx 83$ s and $P_1 \approx 7.7$ s. As before, we accounted for the observed frequency evolution from $\nu_1 = 0.124$ Hz to 0.132 Hz (Mauche 1996) by scaling the frequency vectors of the 37 power spectra by the instantaneous frequency of the dominant ν_1 oscillation. The mean of these scaled power spectra is shown in the lower panel of Figure 2. Note that most of the power of the ν_1 oscillation again lies in a single frequency bin, there is no excess power in the first harmonic $2\nu_1$ or subharmonic $\nu_1/2$ (i.e., the dominant ν_1 oscillation is sinusoidal to high degree), and the lower-frequency peak lies at $\nu_0/\nu_1 \approx 0.096$.

2.3. Energy Dependence of the DNOs

Before leaving this section, we note that it is possible to use the *Chandra* LETG data to investigate the energy dependence of the EUV/soft X-ray oscillations of SS Cyg. While an Å-by-Å investigation of the spectrum of the oscillations is beyond the scope of this paper, it is a simple matter to divide the LETG soft X-ray bandpass in two. A division at $\lambda \approx 80$ Å would halve the counts from the soft component of the X-ray spectrum of SS Cyg, but instead we divided the counts at $\lambda = 70$ Å to approximate the bandpass of the *EUVE* DS. As before, we constructed background-subtracted light curves with 1 s time resolution, divided the light curves into 47 consecutive 1 ks intervals, calculated power spectra, and derived mean power spectra. The resulting mean power spectra for the $\lambda = 42\text{--}70$ Å and $\lambda = 70\text{--}120$ Å bandpasses are shown respectively in the upper and lower panels of Figure 3. This figure shows that in the softer $\lambda = 70\text{--}120$ Å bandpass the $\nu_0 \approx 0.0090$ Hz and $\nu_1 \approx 0.11$ Hz oscillations are slightly stronger, while in the harder $\lambda = 42\text{--}70$ Å bandpass the shoulder on the $\nu_1 \approx 0.11$ Hz oscillation appears to resolve into a distinct peak at $\nu_2 \approx 0.12$ Hz.

3. Discussion

3.1. CV DNOs and QPOs

Summarizing the results from the previous section, we have found that during the 1994 June/July *EUVE* observation of SS Cyg in outburst the EUV flux was oscillating at frequencies $\nu_0 \approx 0.012$ Hz and $\nu_1 \approx 0.13$ Hz, while during the 2001 January *Chandra* LETG observation the soft X-ray flux was oscillating at frequencies $\nu_0 \approx 0.0090$ Hz, $\nu_1 \approx 0.11$ Hz, and possibly $\nu_2 \approx \nu_0 + \nu_1 \approx 0.12$ Hz. We note that because the frequency of the ν_0 oscillation is not constant from 1994 to 2001, it cannot be due to the spin of the white dwarf, as suggested by Mauche (1997b). Instead, the near-constancy of the ratio $\nu_0/\nu_1 \approx 0.09$ suggests that the ν_0 oscillation is related to the dominant ν_1 oscillation.

To place these results in a broader context, we note that other high- \dot{M} CVs have been observed to display multiple periodicities in their power spectra. First, Woudt & Warner (2002) list a number of instances in the literature when pairs of DNOs have been detected in the optical flux of nova-like variables and dwarf novae in outburst. Second, Steeghs et al. (2001) detected a pair of DNOs at $\nu_1 = 0.0336$ Hz and $\nu_2 = 0.0356$ Hz in the optical continuum and Balmer emission line flux of V2051 Oph during its 1998 July outburst. Although it was not possible to detect the difference frequency $\nu_2 - \nu_1 = 0.002$ Hz directly in the power spectrum (D. Steeghs 2002, personal communication), the amplitude of the oscillation varied considerably on a timescale equal to the inverse of the difference frequency (8 min). Third, Woudt & Warner (2002) discuss a number of instances when multiple periodicities have been detected in the optical flux of VW Hyi in outburst. During the decline of the 2000 February outburst, DNOs with periods $P_{\text{DNO}} = 27\text{--}37$ s and QPOs with periods $P_{\text{QPO}} = 400\text{--}$

580 s were detected simultaneously. The ratio $P_{\text{DNO}}/P_{\text{QPO}} = 0.064\text{--}0.071$, which is similar to the ratio observed in the EUV and soft X-ray oscillations of SS Cyg. Furthermore, in data from the 1972 November outburst of VW Hyi, three oscillations were detected simultaneously: a pair of DNOs with periods $P_1 = 28.77$ s and $P_2 = 31.16$ s, and a QPO with a period $P_{\text{QPO}} = 349$ s. The ratio $P_2/P_{\text{QPO}} = 0.089$ and the difference frequency $1/P_1 - 1/P_2 = 0.00267$ Hz, which is close, but not equal, to the QPO frequency $1/P_{\text{QPO}} = 0.00287$ Hz.

3.2. Possible Connection Between CV and LMXB QPOs

Having established these properties of the QPOs of CVs, it is interesting to investigate their possible connection to the QPOs of LMXBs. van der Klis (2000) provides a comprehensive review of LMXB QPOs, so it is sufficient to note here that among neutron star binaries, the luminous Z sources have pairs of 200–1200 Hz “kilohertz QPOs,” 15–60 Hz “horizontal branch oscillations” (HBOs), and 5–20 Hz “normal branch oscillations,” while the less luminous atoll sources have 500–1250 Hz kilohertz QPOs, as well as 20–60 Hz QPOs and broad noise components with properties that are similar to HBOs. ?)hereafter PBK99]psa99 showed that in five Z sources a tight correlation exists between the HBO frequency ν_{HBO} and the frequency ν_l of the lower-frequency member of the pair of kHz QPOs (the “lower kHz QPO”). Specifically, when $\nu_l \lesssim 550$ Hz, $\nu_{\text{HBO}} \approx 0.12 \nu_l^{0.95 \pm 0.16}$. Furthermore, by identifying with ν_{HBO} and ν_l the frequencies of various types of peaked noise components in atoll sources, other neutron star binaries, and black hole binaries, PBK99 and subsequently ?)hereafter BPK02]bel02 extended this correlation over nearly three orders of magnitude in frequency. As noted by Warner & Woudt (2002a,b), the optical data for VW Hyi in outburst lie on an extrapolation of this correlation, extending it an additional two orders of magnitude in frequency. Figure 4 shows that our EUV and soft X-ray data for SS Cyg in outburst also lie on an extrapolation of this correlation, further establishing the connection between the CV and LMXB QPOs.

This connection identifies the DNOs of CVs with the kHz QPOs of LMXBs, and the QPOs of CVs with the HBOs (or the broad noise component identified as such) of LMXBs. We note that the frequencies of the DNOs of CVs and the kHz QPOs of neutron star binaries are similar in that they are comparable to the Keplerian frequency $\nu_K(r) = \frac{1}{2\pi}(GM_\star/r^3)^{1/2}$ at the inner edge of the accretion disk of, respectively, a white dwarf and neutron star: $\nu_K \leq 0.14$ Hz for a $M_\star = 1 M_\odot$ white dwarf with $r \geq R_\star = 5.5 \times 10^8$ cm, while $\nu_K \lesssim 1570$ Hz for a $M_\star = 1.4 M_\odot$ neutron star with $r \gtrsim 3 R_S = 6 GM_\star/c^2 = 12.4$ km, as required by general relativity. In addition to their frequencies, the DNOs of CVs and the kHz QPOs of neutron star binaries are similar in that they have relatively high coherence and high amplitudes, their frequency scales with the inferred mass-accretion rate, and they sometimes occur in pairs.

3.3. Implications for QPO Models

Given the apparent connection between the QPOs of white dwarf, neutron star, and black hole binaries, it is appropriate that we investigate the implications for the theories of QPO formation. In the beat-frequency models, QPOs occur at the Keplerian frequency $\nu_K(r)$ at a special radius in the accretion disk, and the beat of this frequency with the stellar rotation frequency ν_* . In the magnetospheric beat-frequency model (Alpar & Shaham 1985; Lamb et al. 1985), the HBO frequency is identified with the beat frequency between the Keplerian frequency at the magnetospheric radius r_m and the stellar rotation frequency: $\nu_{\text{HBO}} = \nu_K(r_m) - \nu_*$. In the sonic-point beat-frequency model (Miller, Lamb, & Psaltis 1998), some of the disk plasma makes its way past the magnetospheric radius to the “sonic point” radius r_s where the disk is effectively terminated because of either radiation drag or general relativistic corrections to Newtonian gravity. In this model, the upper kHz QPO frequency is identified with the Keplerian frequency at the sonic point radius: $\nu_u = \nu_K(r_s)$, and the lower kHz QPO frequency is identified with (one or two times) the beat frequency between the Keplerian frequency at the sonic point radius and the stellar rotation frequency: $\nu_l = n[\nu_K(r_s) - \nu_*]$, where $n = 1$ or 2 . Note that in this model, the stellar rotation frequency $\nu_* = (n\nu_u - \nu_l)/n$. In the relativistic precession model (Stella & Vietri 1998, 1999), the QPO signals are due to the fundamental frequencies of disk plasma orbiting a rapidly rotating compact star in slightly eccentric and tilted orbits. In this model, the upper kHz QPO frequency is identified with the Keplerian frequency: $\nu_u = \nu_K$, the lower kHz QPO frequency is identified with the periastron precession frequency: $\nu_l = \nu_{\text{pp}}$, and the HBO frequency is identified with the nodal precession frequency: $\nu_{\text{HBO}} = \nu_{\text{np}}$.

How does the existence of QPOs in white dwarf, neutron star, and black hole binaries constrain the theories of QPO formation? First, as has been pointed out by other authors, the existence of QPOs in both neutron star and black hole binaries excludes both flavors of the beat-frequency models (as well as *any* model requiring the presence or absence of a stellar surface or magnetic field). Second, the DNOs of CVs exclude the sonic-point beat-frequency model. First, there is no reason to expect a sonic point in the inner disk of a CV: $R_* > 3R_g$ and radiation drag is unimportant because the luminosity is a small fraction of the Eddington rate ($L \approx GM_*\dot{M}/2R_* \lesssim 3 \times 10^{35} \text{ erg s}^{-1} \approx 0.002 L_{\text{Edd}}$) and because the flow is only mildly relativistic ($v_K \lesssim [GM_*/R_*]^{1/2} \lesssim 0.02c$). Second, in VW Hyi at least, the DNO frequency separation is not equal to one or two times the white dwarf spin frequency. Using the *Hubble Space Telescope* (HST) Goddard High Resolution Spectrograph, Sion et al. (1995) measured the projected rotation velocity of the white dwarf in VW Hyi in quiescence to be $v \sin i \approx 600 \text{ km s}^{-1}$. With a binary inclination $i \approx 60^\circ$ and a white dwarf mass $M_* = 0.63 M_\odot$ (hence $R_* = 8.4 \times 10^8 \text{ cm}$), $\nu_* = v/2\pi R_* \approx 0.013 \text{ Hz}$, whereas the DNO separation frequency $\nu_u - \nu_l \approx 0.00267 \text{ Hz}$. Third, the QPOs and DNOs of CVs exclude the relativistic precession model. First consider the nodal precession frequency, which is the sum of the relativistic (Lense-Thirring) precession frequency ν_{LT} due to frame dragging around a rapidly rotating compact star and the classical precession frequency ν_{cl} due to the quadrupole term in the gravitational potential of an oblate star. Because ν_{cl} is negative for prograde orbits, $\nu_{\text{np}} \leq \nu_{\text{LT}} =$

$8\pi^2\nu_K^2\nu_\star I_\star/M_\star c^2$, where $I_\star \approx 0.1 M_\star R_\star^2$ is the moment of inertia of the star. For a $M_\star = 1 M_\odot$ white dwarf, $\nu_K \leq 0.14$ Hz and $I_\star \approx 6 \times 10^{49}$ g cm², and since stability requires $\nu_\star < \nu_K$, $\nu_{\text{np}} \lesssim 10^{-5}$ Hz, whereas the observed CV QPO frequencies $\nu_{\text{QPO}} \gtrsim 10^{-3}$ Hz. Next consider the periastron precession frequency, which is the difference between the Keplerian and epicyclic frequencies. The latter term is $\nu_r \approx \nu_K (1 - 6 GM_\star/c^2 r)^{1/2}$ to sufficient accuracy for a white dwarf accretor, so $\nu_{\text{pp}} \approx \nu_K [1 - (1 - 6 GM_\star/c^2 r)^{1/2}] \lesssim 10^{-3}$ Hz, whereas the observed CV DNO frequencies $\nu_{\text{DNO}} \gtrsim 10^{-2}$ Hz.

In summary, assuming that the same mechanisms produce the QPOs in white dwarf, neutron star, and black hole binaries, we find that the data exclude the relativistic precession model and the magnetospheric and sonic-point beat-frequency models (as well as *any* model requiring the presence or absence of a stellar surface or magnetic field). More promising are models, such as the transition layer model of Titarchuk and collaborators (Titarchuk, Lapidus, & Muslimov 1998; Titarchuk, Osherovich, & Kuznetsov 1999; Titarchuk & Wood 2002), that interpret QPOs as manifestations of disk accretion onto any low-magnetic field compact object.

3.4. Conclusion

The results from the previous sections suggest that there is a close relationship between the QPOs of CVs and LMXBs, with the DNOs of CVs being the analogues of the kHz QPOs of LMXBs and the QPOs of CVs being the analogues of the HBOs (or the broad noise component identified as such) of LMXBs. The proposed equivalence of CV DNOs and LMXB kHz QPOs strengthens the commonly-held belief that the frequency of the kHz QPOs is equal to the Keplerian frequency at the inner edge of the accretion disk because (1) the frequency ratio $\nu_{\text{DNO}}/\nu_{\text{kHz}} \approx \nu_K(R_{\text{WD}})/\nu_K(R_{\text{NS}}) = (M_{\text{WD}}/M_{\text{NS}})^{1/2}(R_{\text{NS}}/R_{\text{WD}})^{3/2} \approx 10^{-4}$ and (2) in every case the DNO frequencies are consistent with the requirement that $\nu_{\text{DNO}} \leq \nu_K(R_{\text{WD}})$ (Patterson 1981; Knigge et al. 1998). The proposed equivalence of CV DNOs and LMXB kHz QPOs on one hand and CV QPOs and LMXB HBOs on the other hand can be strengthened by finding more CVs with pairs of DNOs and more CVs in which DNOs and QPOs are observed simultaneously. Conversely, systems known to show only QPOs could be searched more carefully for DNOs. A interesting candidate is the dwarf nova U Gem in outburst, whose ≈ 0.04 Hz QPO (Córdova et al. 1984; Mason et al. 1988; Long et al. 1996) implies the existence of ≈ 0.5 Hz (2 s) DNOs (an oscillation period shorter than the integration times typically employed to search for optical oscillations). For the Keplerian frequency to be this high, the mass of the white dwarf in U Gem must be quite high: $M_\star \gtrsim 1.3 M_\odot$, assuming the Nauenberg (1972) white dwarf mass-radius relation. This requirement is consistent with the white dwarf mass derived by Friend et al. (1990) ($M_\star = 1.26 \pm 0.12 M_\odot$), but is inconsistent with the values derived by Long & Gililand (1999) ($M_\star = 1.14 \pm 0.07 M_\odot$) and Smak (2001) ($M_\star = 1.07 \pm 0.08 M_\odot$).

Aside from filling in the lower-left corner of Figure 4, additional observations of CVs are warranted because they provide unique and quantitative tests of QPO models. Data can be obtained from the ground in the optical and from space in the ultraviolet, EUV, and soft X-rays; the

system parameters (binary inclination, white dwarf mass, radius, and rotation velocity) can be measured; eclipse mapping in edge-on systems allows the sites of flux modulations to be located and dissected; dwarf nova outbursts provide a dramatic and systematic variation in the mass-accretion rate; diagnostic emission lines are available from the optical through soft X-rays, and general relativistic effects are minimal. Furthermore, technological improvements now allow *spectroscopic* observations of the flux oscillations of CVs. Steeghs et al. (2001) used the Keck Low Resolution Imaging Spectrograph ($\lambda = 3600\text{--}9200\text{ \AA}$) in continuous readout mode to study the DNOs in the optical continuum and Balmer line flux of the eclipsing dwarf nova V2051 Oph in outburst. Marsh & Horne (1998) used the *HST* Faint Object Spectrograph with the G160L ($\lambda = 1150\text{--}2510\text{ \AA}$) grating to study the wavelength dependence of the ultraviolet DNOs of the eclipsing dwarf nova OY Car in outburst. Mauche (2002b) used the *HST* Space Telescope Imaging Spectrograph in time-tag mode with the E140H ($\lambda = 1495\text{--}1690\text{ \AA}$) echelle grating to study the ultraviolet DNOs of SS Cyg in outburst, while Mauche (1997a) used the *EUVE* SW spectrometer to study the wavelength dependence of the EUV DNOs of SS Cyg in outburst. Such observations shed new light on the QPOs of CVs and LMXBs.

4. Summary

We have shown that during the 1994 June/July *EUVE* observation of SS Cyg in outburst the EUV flux was oscillating at frequencies $\nu_0 \approx 0.012\text{ Hz}$ and $\nu_1 \approx 0.13\text{ Hz}$, while during the 2001 January *Chandra* LETG observation the soft X-ray flux was oscillating at frequencies $\nu_0 \approx 0.0090\text{ Hz}$, $\nu_1 \approx 0.11\text{ Hz}$, and possibly $\nu_2 \approx \nu_0 + \nu_1 \approx 0.12\text{ Hz}$. These data, combined with the optical data of Woudt & Warner (2002) for VW Hyi, extend the PBK99 and BPK02 $\nu_{\text{high}}\text{--}\nu_{\text{low}}$ correlation for neutron star and black hole LMXBs nearly two orders of magnitude in frequency, with $\nu_{\text{low}} \approx 0.08 \nu_{\text{high}}$. This correlation identifies the DNOs of CVs with the kHz QPOs of LMXBs, and the QPOs of CVs with the HBOs (or the broad noise component identified as such) of LMXBs. Assuming that the same mechanisms produce the QPOs in white dwarf, neutron star, and black hole binaries, we find that the data exclude the relativistic precession model and the magnetospheric and sonic-point beat-frequency models (as well as *any* model requiring the presence or absence of a stellar surface or magnetic field). Additional observations of CVs can help establish the proposed equivalence of CV and LMXB QPOs, and will provide unique and quantitative tests of QPO models.

Our satellite observations of SS Cyg were made possible by the optical monitoring and alerts provided by the members, staff (particularly E. Waagen), and director, J. Mattei, of the American Association of Variable Star Observers. The *EUVE* observation was made possible by the efforts of *EUVE* Project Scientist R. Malina, Science Planner M. Eckert, the staff of the *EUVE* Science Operations Center at the Center for EUV Astrophysics, and the Flight Operations Team at Goddard Space Flight Center. The *Chandra* observation was made possible by the efforts of *Chandra* X-Ray Observatory Center Director H. Tananbaum, Mission Planner K. Delain, and the *Chandra* Flight

Operations Team at MIT. We acknowledge T. Belloni for kindly supplying us with the neutron star and black hole binary data shown in Figure 4; L. Titarchuk, K. Wood, and D. Steeghs for helpful discussions; and the anonymous referee for comments which improved the clarity of the manuscript. Support for this work was provided by NASA through *Chandra* Award Number GO1-2023A issued by the *Chandra* X-Ray Observatory Center, which is operated by the Smithsonian Astrophysical Observatory for and on behalf of NASA under contract NAS8-39073. This work was performed under the auspices of the U.S. Department of Energy by University of California Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

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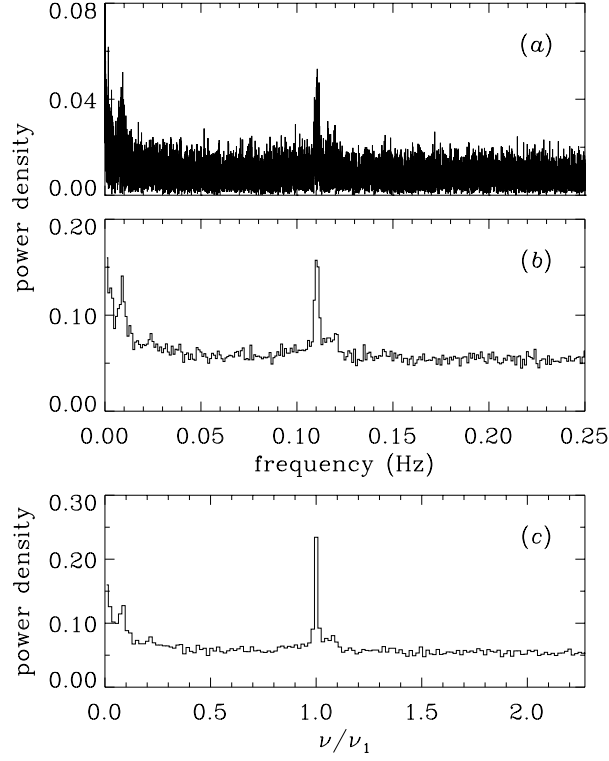


Fig. 1.— Power spectra of *Chandra* LETG $\lambda = 42\text{--}120$ Å count rate light curves of SS Cyg in outburst. (a) Power spectrum of 47 ks of data binned to 1 s time resolution. (b) Mean power spectrum of 47 consecutive 1 ks light curves. (c) Mean power spectrum of the 47 1 ks light curves after scaling by the varying frequency of the $\nu_1 \approx 0.11$ Hz oscillation. Note the simultaneous presence of oscillations at $\nu_0 \approx 0.0090$ Hz, $\nu_1 \approx 0.11$ Hz ($\nu_0/\nu_1 \approx 0.088$), and possibly a third at $\nu_2 \approx \nu_0 + \nu_1 \approx 0.12$ Hz.

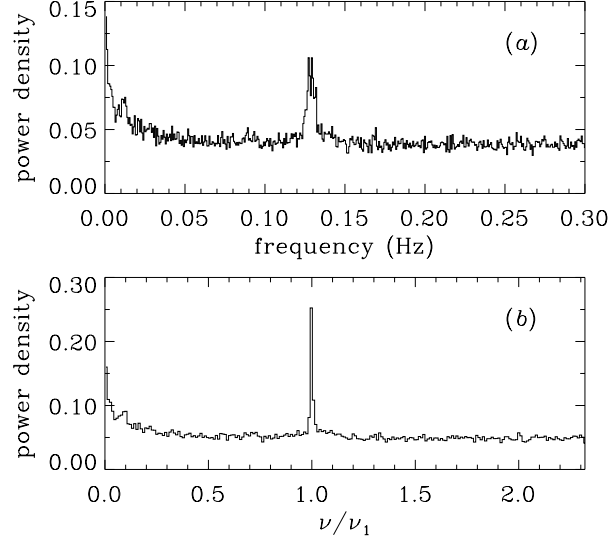


Fig. 2.— Power spectra of *EUVE* DS count rate light curves of SS Cyg in outburst. (a) Mean power spectrum of 37 1.5 ks light curves. (b) Mean of the 37 1.5 ks light curves after scaling by the varying frequency of the $\nu_1 \approx 0.13$ Hz oscillation. Note the simultaneous presence of oscillations at $\nu_0 \approx 0.012$ Hz and $\nu_1 \approx 0.13$ Hz ($\nu_0/\nu_1 \approx 0.096$).

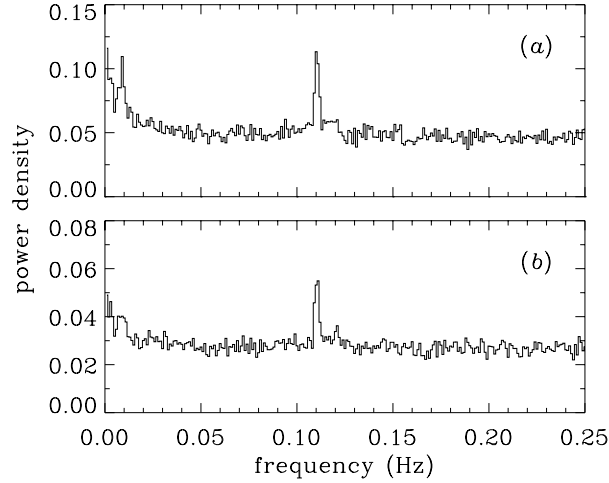


Fig. 3.— Mean power spectra of 47 consecutive 1 ks *Chandra* LETG count rate light curves of SS Cyg in outburst in the (a) soft $\lambda = 70\text{--}120$ Å and (b) hard $\lambda = 42\text{--}70$ Å bandpasses. Note that the $\nu_0 \approx 0.0090$ Hz and $\nu_1 \approx 0.11$ Hz oscillations are slightly stronger in the soft bandpass, and that there is evidence for a distinct oscillation at $\nu_2 \approx \nu_0 + \nu_1 \approx 0.12$ Hz in the hard bandpass.

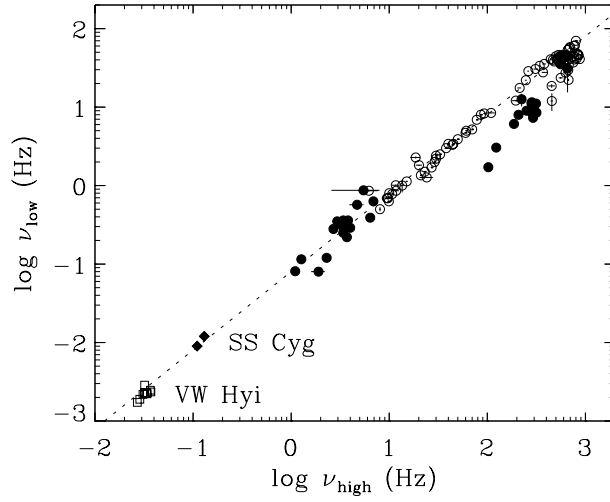


Fig. 4.— $\nu_{\text{high}}\text{--}\nu_{\text{low}}$ correlation for neutron star binaries (*open circles*), black hole binaries (*filled circles*), and the white dwarf binaries SS Cyg (*filled diamonds*) and VW Hyi (*open squares*). Neutron star and black hole binary data are from Figure 12 of BPK02, and were kindly supplied by T. Belloni. Dotted line drawn through the points is $\nu_{\text{low}} = 0.08 \nu_{\text{high}}$.